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17 JAN 1997

FABRICATION OF A 20.5 INCH DIAMETER SEGMENTED SILICON ANNULAR OPTIC PROTOTYPE FOR THE ROMA PROGRAM

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Abstract

Recent advancements in single crystal silicon material science and fabrication capabilities and very low absorption (VLA) multi-layer dielectric coating technology have led to the development of uncooled, large aperture, high power mirrors for high energy laser (HEL) systems. Based on this success, a segmented single-crystal silicon substrate concept has been selected as the baseline fabrication approach for uncooled 1.2 meter diameter resonator annular optics for the Alpha space based high energy laser. The objective of this Resonator Optics Materials Assessment (ROMA) task was to demonstrate all of the key fabrication processes required to fabricate the full sized annular optics for the Alpha space based high energy laser. This paper documents the fabrication of a half-scale annular optic prototype (AOP) of the Alpha laser rear cone.

Key words: laser, resonator, annular optic, beam compactor, rear cone, molybdenum, silicon, silicon carbide, Alpha.

1. Description of the Alpha Resonator Annular Optics

The Alpha laser is a ground-based demonstration of one of the key technologies of a space-based chemical laser. The Alpha optical resonator subsystem employs two state-of-the-art, 1.2 meter diameter cooled molybdenum annular optics with single-point diamond-turned conical shapes coated with a single-layer dielectric coating.

The Alpha annular optics consist of the beam compactor outer cone and the rear cone. These optical assemblies shown in Figure 1 have an optical clear aperture of 46.5 inches diameter and an overall diameter of 50.8 inches. For Alpha, each 580 pound optical substrate was constructed of molybdenum with three layers of counter flowing heat exchangers under each of the optical surfaces. The heat exchanger is necessary to minimize distortion of the optical surfaces due to absorbed energy through the single layer optical coatings. Each annular optic heat exchanger requires a high water coolant flow rate with a substantial heat exchanger pressure drop. This high coolant flow rate requires large diameter plumbing, a complex manifolding scheme, and a high pressure pumping and tanking system. The resulting high velocity of the coolant water causes jitter in the cooled optics and the large pressure drop causes pressure induced distortion of the optical surfaces.

The development of the Large Optics Diamond Turning Machine (LODTM) at Lawrence Livermore National Laboratory (LLNL), as shown in Figure 2, made possible the fabrication of the Alpha diffraction-limited aspheric conical infrared optics. Single point diamond turning (SPDT) is one of the key manufacturing processes for achieving the optical tolerances of the Alpha annular optical system. LODTM is the only facility capable of processing resonator optics of the required size and accuracy, machined to final figure and finish, without requiring subsequent optical polishing. In addition, LODTM also allows on machine inspection of the optical surfaces to the required optical tolerances. Since molybdenum is not directly diamond turnable, each optical surface was clad with a thin layer of UBAC electrodeposited copper to allow for SPDT.

2. Uncooled Annular Optic Development

To reduce the optic weight and eliminate coolant induced jitter, it is desirable to design and fabricate uncooled annular optics. Eliminating the active cooling system also reduces total laser system weight and complexity of the coolant pumping and storage equipment. To fabricate a large diameter (1.2 m) Alpha resonator annular optic, it is presently necessary to bond segments of silicon or silicon carbide to form the annular optic substrate. Two demonstrated bonding techniques; glass-frit bonding and metal-braze bonding were assessed. Since adequate data on bond strength was available, the assessment focused on the impact of the bond joints on SPDT and the very low absorbing (VLA) multilayer dielectric coating (MLDC) performance.

Rockwell Power Systems (RPS) and United Technology Optics Systems (UTOS), having previously demonstrated bonding silicon and silicon carbide for use as optical components, were subcontracted to provide 2-inch diameter bonded witness samples for evaluation.

2.1 Glass-Frit Bonded Witness Samples

RPS developed a proprietary glass-frit bonding process for joining silicon wherein the glass frit was custom made to have desired thermal expansion properties. The parts were fixtured with a dead weight loading scheme and heated up to the glass frit softening temperature. The glass frit fused together with a bond stronger than the parent silicon material.

Each witness sample was chemically etched to remove the subsurface damage layer. The etching did not attack the bond line, resulting in a raised glass-bond line relative to the substrate material. This raised glass line was ground away on both sides of the witness samples. This process also eliminated all bond joint defects that were equal or lesser in depth.

The samples were blocked and the backsides conventionally polished in the TRW Optical Shop to provide a flat mounting surface for mounting the samples to PERL vacuum check at LLNL during SPDT. The glass frit was not as hard as single-crystal silicon, so, after polishing, the bond gap was below the optical surface; not atypical of this material.

2.2 Metal-Braze Bonded Witness Samples

UTOS developed a proprietary Transient Liquid Phase (TLP) bonding process that used a metallic filler material to bond both silicon and silicon carbide. The metallic bonding was affected at a temperature hundreds of degrees cooler than glass-frit bonding. The samples were heated to a temperature high enough to wet the silicon or silicon carbide, resulting in a bond joint stronger than the parent material.

One bonded silicon sample was conventionally polished in the TRW Optical Shop and the bond joint inspected. As with the RPS sample, the bond material was polished below the optical surface. The metallic bond joint was typically 1 mil wide and contained no bond joint defects.

2.3 Elemental Silicon Cladding

Silicon carbide was one of the substrate material candidates selected to be investigated for uncooled annular optics. Silicon carbide may be conventionally polished with diamond based grinding and polishing compounds but is not directly diamond turnable due to its extreme hardness. Based on past experience with several cladding materials for SiC, a physical vapor deposition (PVD) process was selected. The PVD process created an amorphous layer of elemental silicon that replicated the substrate surface finish.

The PVD silicon cladding successfully covered all three types of bonded samples; RPS glass-frit bonded silicon, UTOS metallic-bonded silicon, and UTOS metallic-bonded silicon carbide. The cladding on the RPS samples was very good because the surfaces had been optically polished prior to cladding. These clad samples exhibited a very glassy finish compared to the claddings applied to the UTOS silicon and silicon carbide samples. The cladding on the UTOS samples had a much rougher surface finish because the surface was only diamond ground prior to cladding.

2.4 Single Point Diamond Turning

Five witness samples with bond joints were SPDT'd on the Precision Engineering Research Lathe (PERL) at LLNL. The five samples consisted of: 1) single-crystal silicon (SC Si) with the glass-frit bond; 2) SC Si with the glass-frit bond and PVD Si cladding; 3) SC Si with the metallic bond; 4) SC Si with the metallic bond and PVD Si cladding; and 5) SiC with the metallic bond and PVD Si cladding. All samples had the outer 50 percent of its area SPDT'd in the ductile mode and the remaining area SPDT'd in the microfracture mode.

The unclad glass-frit bonded sample was not directly diamond turnable. The glass bond joint degraded the diamond tool edge, resulting in excessive tool wear and extremely high roughness. This sample is shown on the left side of Figure 3.

The unclad metallic-bonded sample was nearly identical to samples without a bond joint. Tool wear was negligible (less than one microinch) with no edge damage. Surface roughness ranged from 15 to 30 Å in the ductile zone and from 75 to 150 Å rms in the microfracture zone. This sample is shown on the right side of Figure 3.

The PVD silicon clad samples were only partially diamond turnable. The PVD silicon cladding increased tool wear and several samples had numerous scratches in the cladding after SPDT.

In summary, metallic-bonded single-crystal silicon, which can be diamond turned directly with no apparent effect on the SPDT results, was selected as the baseline approach to fabricate a segmented silicon annular optic.

2.4.1 Annular Optic Mini-prototype

Silicon Casting, Inc., regularly produces polycrystal sputter targets resembling the shape of an annular optic optical surface. The 9.7-inch diameter sputter target was provided by Silicon Casting at no cost to the program and was single point diamond turned on LODTM. A parabolic shape that was representative of the rear cone optical contour was generated. Figure 4 shows the mini-AOP mounted on LODTM during the final contour metrology.

2.5 Coating Performance on Bonded Witness Samples

The baseline fabrication approach for annular resonator optics was based on bonded segments. To determine the impact on coating performance, coating absorption was evaluated on and off bond lines for the two bonding techniques and samples with PVD silicon cladding. Eight witness samples were coated in the same coating run with a normal-incidence all-dielectric coating.

Each sample was tested at 2.8 microns by Helios, Inc. for absorption, transmission, and scatter. A comparison of the absorption results showed that SPDT causes absorption more than an order of magnitude higher than conventionally super polished silicon. However, the absorption is reduced for SPDT samples if the substrate is post polished after SPDT. Post polishing ceased when the diamond turning groves started to disappear visually. The mirror surface roughness was reduced without disturbing the optical surface contour. In summary, it was concluded that some post polishing is required to reduce the impact of SPDT in the microfracture regime on VLA coating performance.

SPDT of the PVD silicon cladding has a more detrimental effect on both absorption and scatter whether the substrate is post polished or not. Conventional polishing of the PVD cladding resulted in excellent coating performance, however. The PVD Si cladding on SC Si also was found to reduce transmission through the substrate by a factor of two.

3. Annular Optic Prototype Fabrication

The feasibility of constructing a full-size bonded segmented single-crystal silicon annular substrate as shown in Figure 5 was investigated; it was found that both the cost of the raw silicon material and the size limits of available fabrication facilities (precision diamond machining, chemical milling, brazing furnaces) were cost and risk drivers. The full-sized annular optic substrate would require bonding together 8 single-crystal silicon segments into the rough shape as shown in Figure 6. The individual segments would start out as silicon boules on the order of 10 inches in diameter x 22 inches long.

A demonstration of all the key fabrication processes was performed on a subscale annular optic for much lower cost by utilizing available facilities. A goal was to demonstrate the design and fabrication concepts for an uncooled segmented silicon annular optic by constructing a four-tenths scale prototype, referred to as the annular optic prototype (AOP). The AOP fabrication process is shown in Figure 7.

The design for the 20.5 inch diameter AOP was developed after determining the maximum size that could be built from the lowest cost silicon substrates. The silicon boules were limited to 8 inches in diameter and 15 inches in length for cost considerations.

3.1 Annular Optic Prototype Substrate Segment Fabrication

Silicon Casting, Inc., has demonstrated the capability to produce the large scale silicon boules required for uncooled annular optics, using a computer controlled Czochralski (CZ) puller.

Un-doped 8 inch diameter silicon boules that were in the Silicon Casting inventory were used to minimize cost for the AOP. These boules were single crystal silicon for some of the 15 inch length and transitioned to large-grained polycrystal silicon. In retrospect, the large-grained polycrystal silicon increased the risk of breakage due to the danger of the crystal cleaving along one of the long grain boundaries. Either single-crystal or fine-grained polycrystal silicon should be used in future prototype work, and only single-crystal silicon for an operational annular optic. Silicon Casting provided four rough machined segments as shown in Figure 8.

After rough machining, the segments were chemically milled by TRW to remove any machining damaged surface material.

3.2 Annular Optic Prototype Substrate Segment Match Machining

The rough machined segments were then sent to McCarter Machine Company, Inc. in Pasadena, Texas for match machining into the AOP hexagonal shape as shown in Figure 9. Match machining means that the need for absolute accuracy of any one part is reduced in that each part is machined to match the previous part. This approach is acceptable for AOP prototype work; however, for production optics, standardized parts will be required for complete interchangability of segments. For the AOP, this fabrication approach simplified the machining requirements at both Silicon Casting and McCarter Machine Company and reduced fabrication cost and potential scrapage of material.

The final flatness and angle control on the segments allowed for less than 0.002 inch gap between mating braze surfaces. All segments were lapped flat on the bottom surfaces but the heights of the individual segments varied by approximately 0.200 inches. Some variation in the length of the segments caused steps of approximately 0.200 on the OD fit of the segments, however none of these variations effected the braze and enough machining stock was allowed so that the AOP could still be machined to the full planned size.

3.3 Annular Optic Prototype Braze Tooling Design

Scarrott Metallurgical Company developed the AOP braze material and process parameters. Several candidate braze materials were identified: gold, aluminum, gold/tin alloy, and gold/germanium alloy. Melt tests were performed on silicon sample material and lap joints were brazed on silicon samples. Pure gold and aluminum had the best wetability of the braze material set and were selected for further process development. Aluminum, with the higher braze eutectic temperature showed better wetability and adhesion than could be achieved with gold. The aluminum lap joint samples had braze joints stronger than the silicon material. The gold lap joint samples showed poor wetting compared to the aluminum samples and had low adhesion as evidenced by the lap joints failing at the gold silicon interface. At this point aluminum was selected as the AOP braze material and the braze thermal process parameters were established.

3.4 Annular Optic Prototype Brazing

After match machining, the annular optic prototype segments were brazed. Each silicon segment was cleaned and prepared for the braze stackup. An aluminum braze foil was cut into a 5 inch square and was cleaned by etching. All braze tooling was degreased and all tooling and fiberfrax was heat cycled to bake out any contaminants. The final braze stackup is shown in Figure 10 and the brazed AOP assembly is shown in Figure 11.

3.5 Annular Optic Prototype Post-braze Machining

The brazed AOP was sent to McCarter Machine Company, Inc. for final diamond grinding to the final AOP configuration as shown in Figure 12. The AOP weighed 112.8 pounds after brazing and 66.3 pounds after final machining as shown in Figure 13.

McCarter Machine's horizontal turning lathe was modified to accept a grinding motor in place of the tool station to grind silicon components. The present capability of McCarter is 30 inches in diameter but a larger machine can be brought on line for full sized annular optics. The annular optic prototype grinding required no special tooling to support the optic and to machine the optical contour. The annular optic prototype was manually ground with straight contours to simulate an Alpha rear cone.

The machining process at McCarter demonstrated that a brazed segmented annular optic could be ground to the required shape of an annular optic.

3.6 Annular Optic Prototype Post-machining Processing

The bond joints on the backside surface were found to have some void areas along the bond joint, while the optical surface bond joints were adequate. The single crystal silicon to single crystal silicon joints on the optical surface were the most void free. The cause of the bond joint voids was not completely understood, but since the assembly was still solid, processing was continued.

The backside of the AOP was conventionally optically ground and polished. The goal was to provide an optically flat surface to interface with the LODTM spindle. The backside was optically

polished to less than a wave flat when measured with a 4 inch diameter test plate. No optical surface discontinuities were noted with the test plate over the bond joints. The backside was protected by spraying black Krylon paint over the polished surface.

The AOP was then mounted on a TRW polishing machine used for polishing conical mirrors. The straight optical contour was then optically ground to remove enough material to remove some of the damage layer induced by the McCarter grinding as shown in Figure 14. As with the backside, several of the void areas were cleared up but a couple of the deep pits were not completely removed. The completed AOP was then shipped to LLNL for single point diamond turning.

3.7 Annular Optic Prototype Single-point Diamond Turning

The SPDT of the AOP at LLNL was another step in the continuing development of manufacturing technologies of uncooled aspheric optics. The AOP presented the combined challenges of a longer track length, bond joints interrupting the cuts, a larger than usual amount of stock to be removed, and thermal effects of using water for a cutting fluid. All of these challenges scale with increased size. The LODTM task was to SPDT the AOP to aspheric rear cone optical figure.

The fixturing was designed to minimize the influence of the evaporative cooling by the water. The AOP vacuum chuck fixturing plate was made of Invar 46 with a layer of electroplated copper on mating surfaces. Invar 46 was selected to provide a better match of its CTE to that of silicon. The copper layer allowed the mating surface to be diamond turned flat to match the optically polished base of the AOP without being thick enough to degrade the Invar performance.

The excess stock left for diamond turning on the AOP varied from 0.002 inches to 0.012 inches. The area with the largest amount of excess material was located on the rear cone optical contour surface. In machining this surface, it was determined that it is practical to remove relatively large volumes of silicon by diamond turning. The major concerns were tool wear and material damage. The tool wear in roughing cuts did not turn out to be a major problem. Chipping of the cutting edge was common in these cuts. The chipping that occurred appeared to cause the tool to perform to some degree as a negative rake tool.

The heavy cuts did not appear to the eye to cause increased surface damage in the silicon. By the end of the series of finish cuts, the surface finish of a given segment was most strongly influenced by whether it was single or polycrystalline; and by its orientation, if it were single crystal.

3.7.1 SPDT Results

The AOP reference surface was successfully machined as a reference diameter for the accurate location of surface figure. The runout of the diameter after centering and low pass filtering was less than 3 μinches. The top surface of the AOP was machined to be the vertical axis reference surface. The flatness of the finished top surface was measured and found to have less than 5 μinches of runout.

To finish the optical surface, a series of microfracture cuts was made. Attempts were made between cuts to correct the surface program based on the previous cut's inspection results. These in-process corrections were only partially successful. The finish cuts were made assuming that the time allowed for the machine to come to thermal equilibrium during machining of the silicon conical test articles would be sufficient for the AOP. The measured errors in the contour were compensated for in the next program as tool wear and tool/workpiece deflection errors. These errors sources converged while the thermally induced errors diverged.

The optical surface on the last pass had 41 μinches of slope that accumulated due to the thermal errors. When the thermal induced slope removed from the trace, the contour of the optical surface was contained within a 4.5 μinch band.

3.7.2 SPDT Conclusions

The major conclusion drawn from machining the AOP is that process control will be the key to producing large silicon optics. The process will demand increased awareness of thermal conditions and their management. Future machining of the AOP or other parts should include thermistors mounted on the part and fixturing to provide feedback on the thermal condition of the process.

Removing large amounts of excess stock from the AOP was much less difficult than expected. There is no supporting evidence but it is suspected that the

interrupted cutting at the bond joints contributes to the tool chipping. However, the chipping did not appear to have a large influence on the finish cuts.

The large grain polycrystal silicon has pronounced effect on the surface figure control and caused scratching originating at crystal intersections.

3.8 Annular Optic Prototype Post Polishing

The AOP was mounted on a TRW machine used for polishing conical mirrors. The goal was to post-polish the top reference surface and the figured surface using a conformal lap developed by TRW until the diamond tool marks were just visible. The post-polishing improved the surface finish; when a 4-inch diameter 20th wave visible test plate was laid over the bond joint there was no indication of a bond joint. The areas of polycrystal silicon were also dramatically improved by the post-polishing process.

Conclusion

All of key the fabrication processes for constructing a full-size uncooled silicon annular optic have been demonstrated. The processing of AOP is summarized in Figures 15 and 16. The next step is to scale up the facilities and equipment for the full sized components.

Acknowledgements

The Resonator Optics Materials Assessment (ROMA) program was performed on the TRW Space and Defense, Zenith Star contract number GH8-180564 to Lockheed Martin Astronautics under their Zenith Star prime contract number SDIO-89-C-0003 to the Ballistic Missile Defense Office (BMDO).

The author would like to thank Dr. Lyn Skolnik of the Ballistic Missile Defense Office and Mr. Larry Buelow of Lockheed Martin Astronautics for sponsorship, and Dr. Larry Zajac, Dr. Bob Field, Dr. Phil Goede, Dr. Bill Goodman, Mr. Bruce Heckert, and Mr. Chris Lieto of W. J. Schafer Associates, Inc., and Dr. Gary Morr of SAIC for their technical assistance. Thanks also go to Dr. Jim Boyle of Silicon Casting Inc. in Rancho Cordova, CA, Mr. Doug McCarter of McCarter Machine Co., Inc. in Pasadena, TX, Mr. Robert Fairbanks of Scarrott Metallurgical Services in Los Angeles, CA, Mr. Matt Chmait of TRW in Redondo Beach, CA, and Mr. Jim Hamilton, Mr. Steve Bretz, and Mr. Charlie Giles of Lawrence Livermore National Laboratory in Livermore, CA for technical contributions.

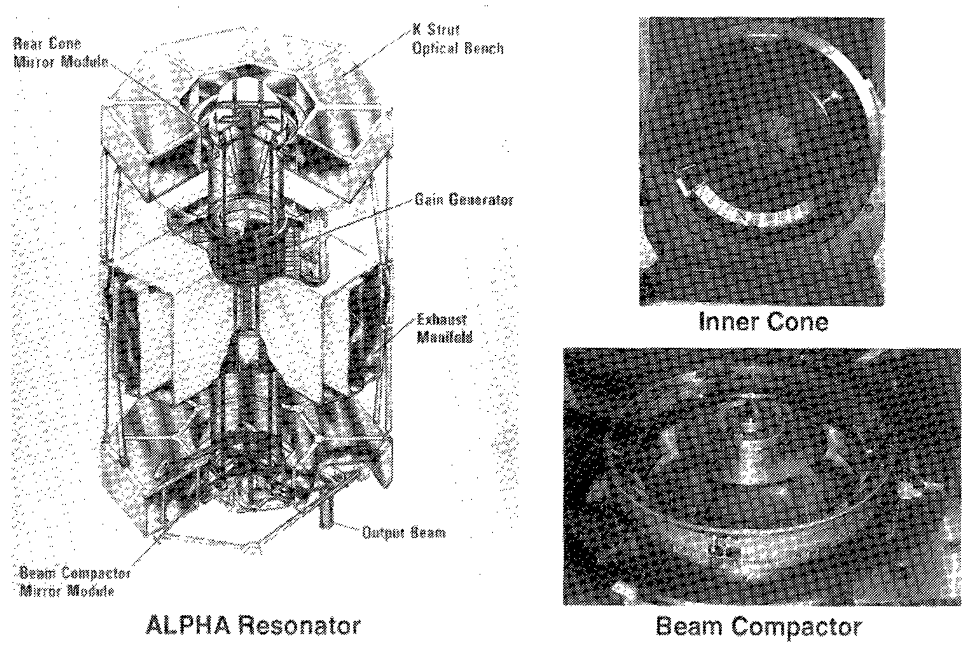

Figure 1. Alpha Annular Optics

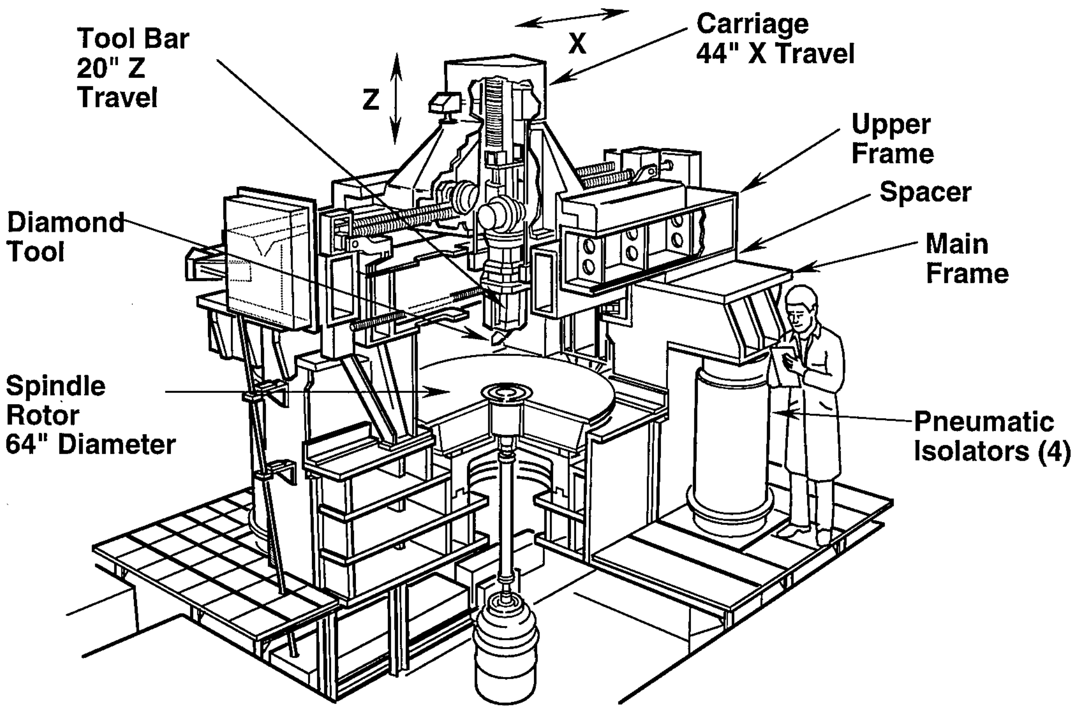

Figure 2. Large Optics Diamond Turning Machine (LODTM)

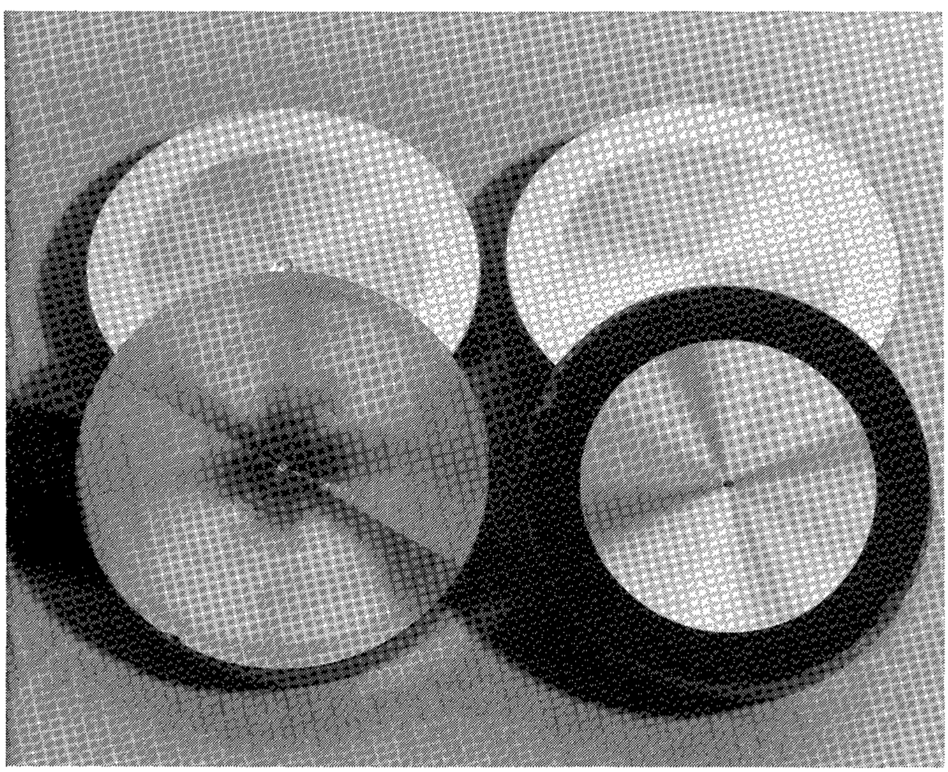

Figure 3. Glass Frit Bonded Samples and Metallic Bonded Samples After SPDT

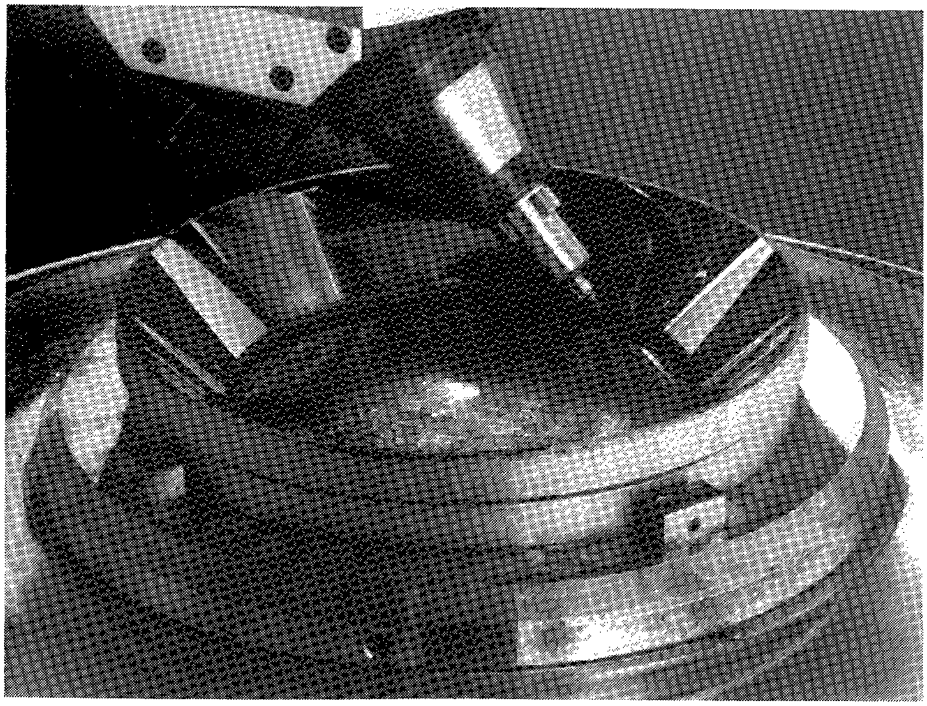

Figure 4. Polycrystal Silicon Sputter Target on LODTM Undergoing Optical Surface Metrology

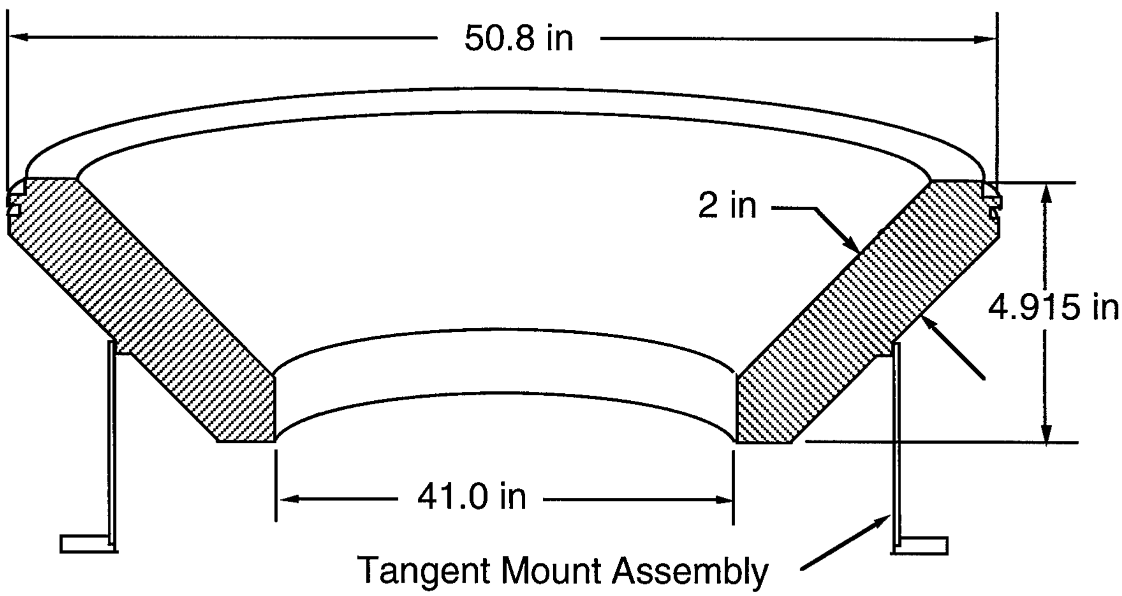

Figure 5. Alpha Annular Optic Substrate Final Shape

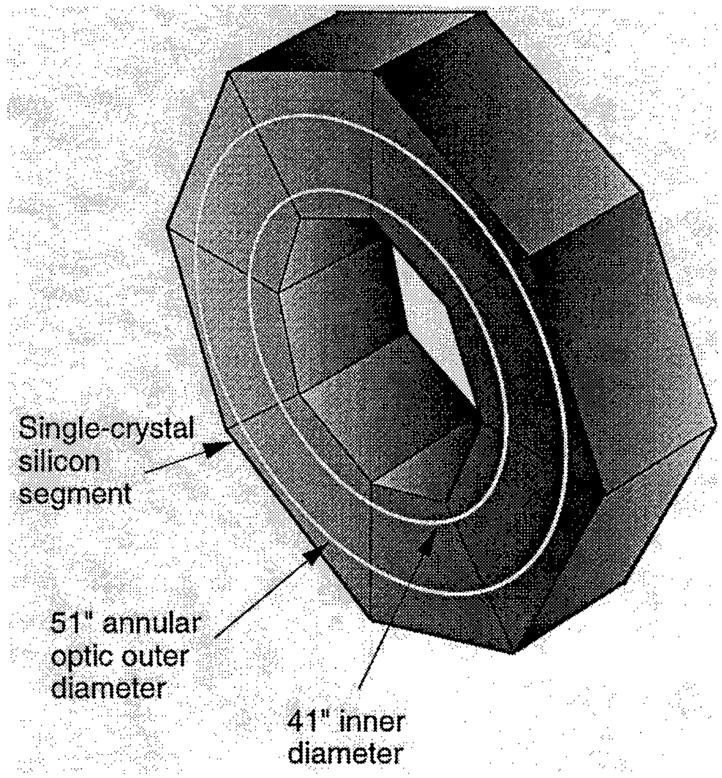

Figure 6. Eight Silicon Segment Annular Optic Substrate Concept

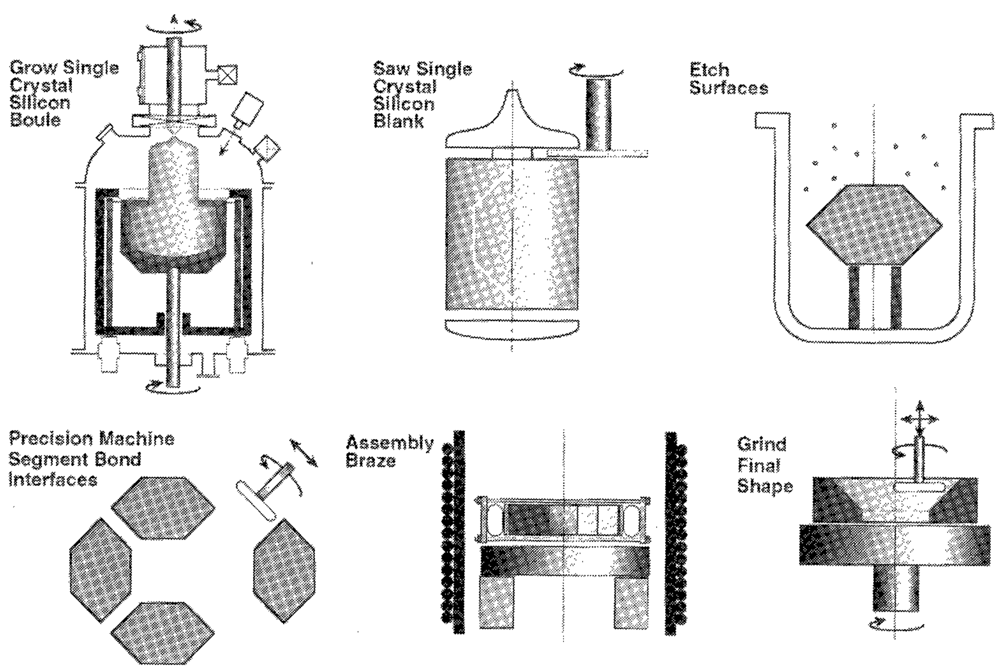

Figure 7. Silicon AOP Fabrication Logic

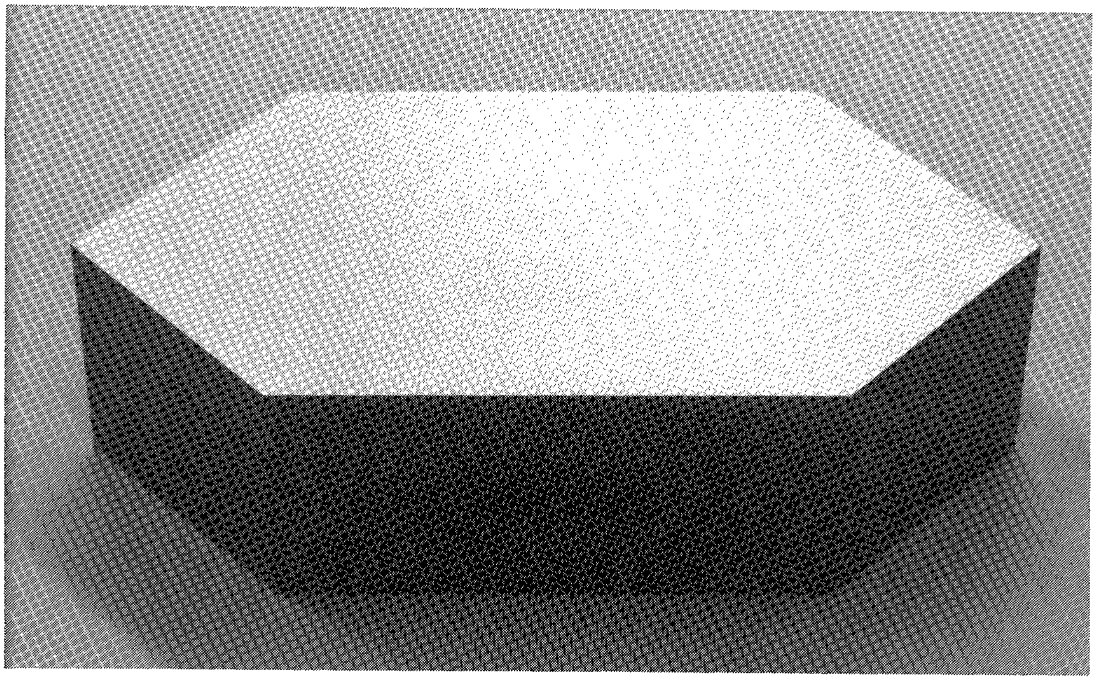

Figure 8. AOP Rough Machined Silicon Segments Provided by Silicon Casting

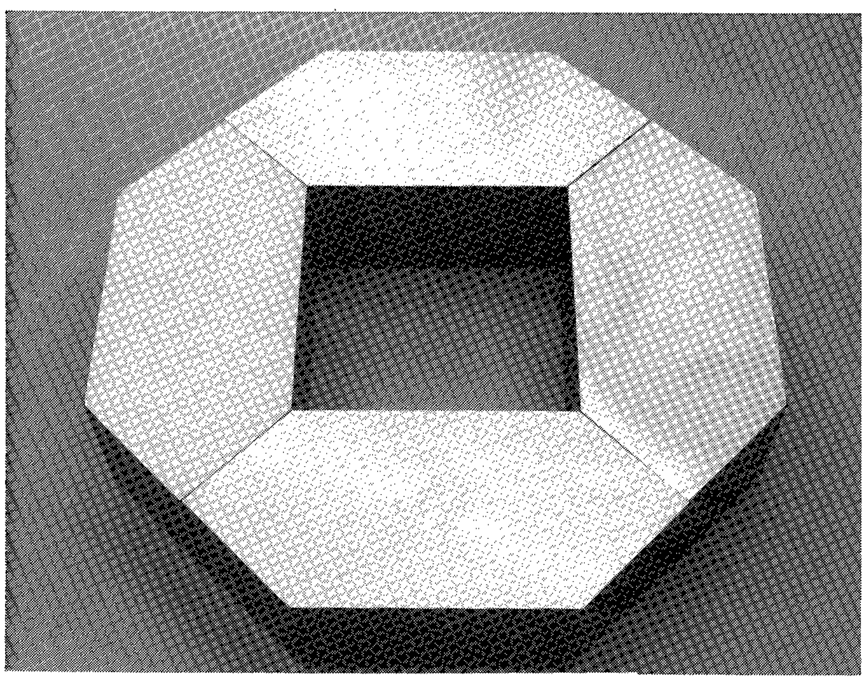

Figure 9. AOP Match Machined Silicon Segments by McCarter Machine

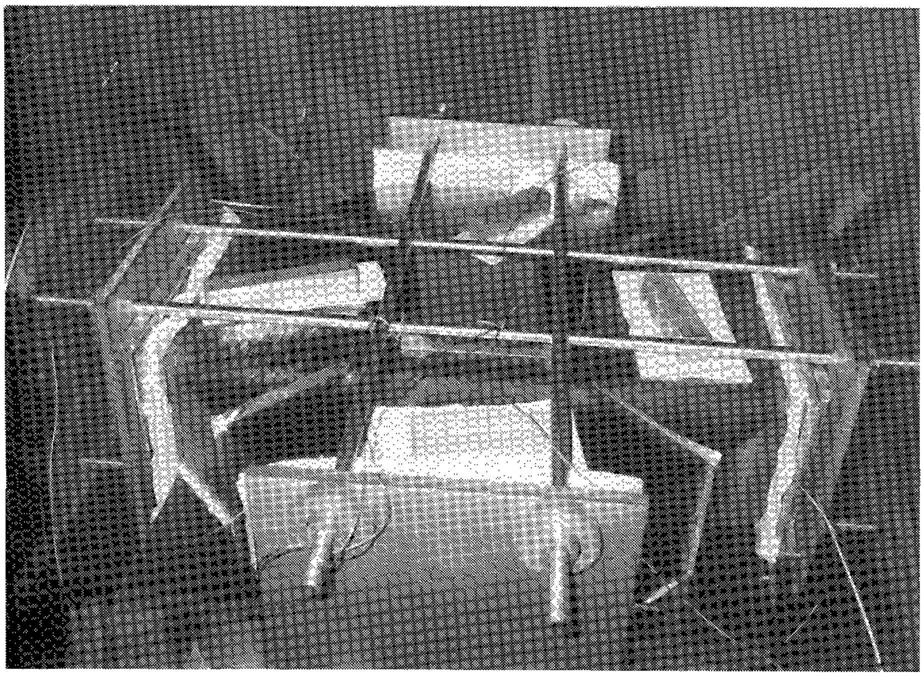

Figure 10. AOP Braze Stack in Furnace at Scarrott

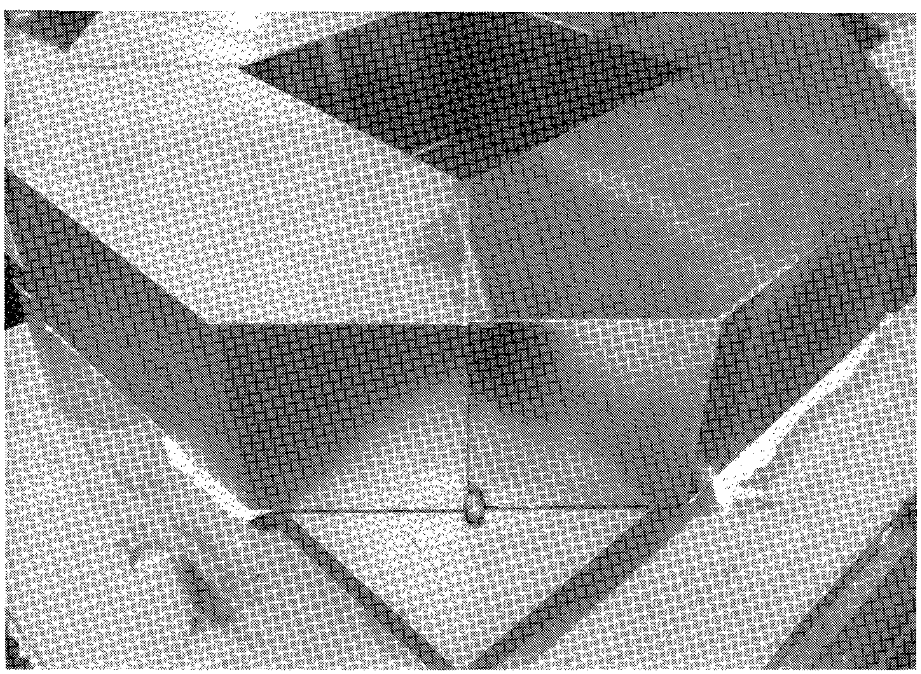

Figure 11. AOP Assembly After Brazing at Scarrott

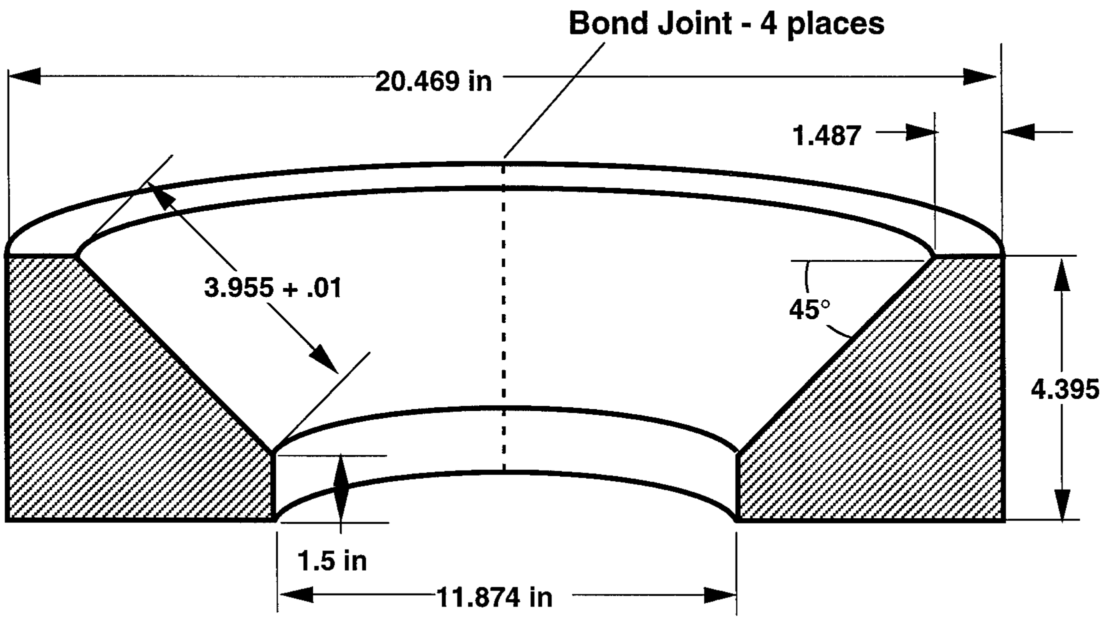

Figure 12. Annular Optic Prototype Final Dimensions

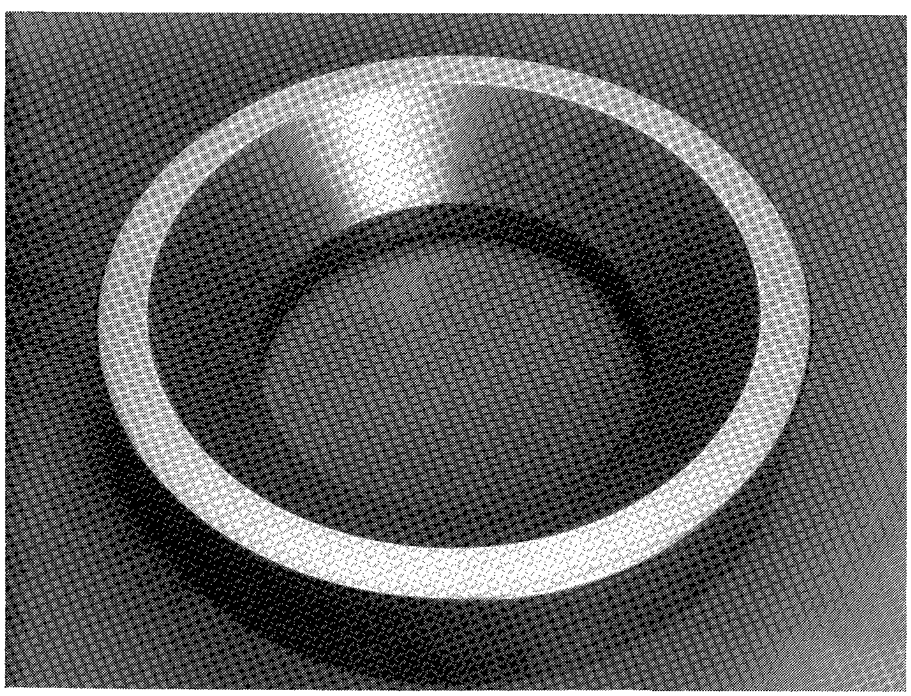

Figure 13. Annular Optic Prototype As-machined by McCarter Machine

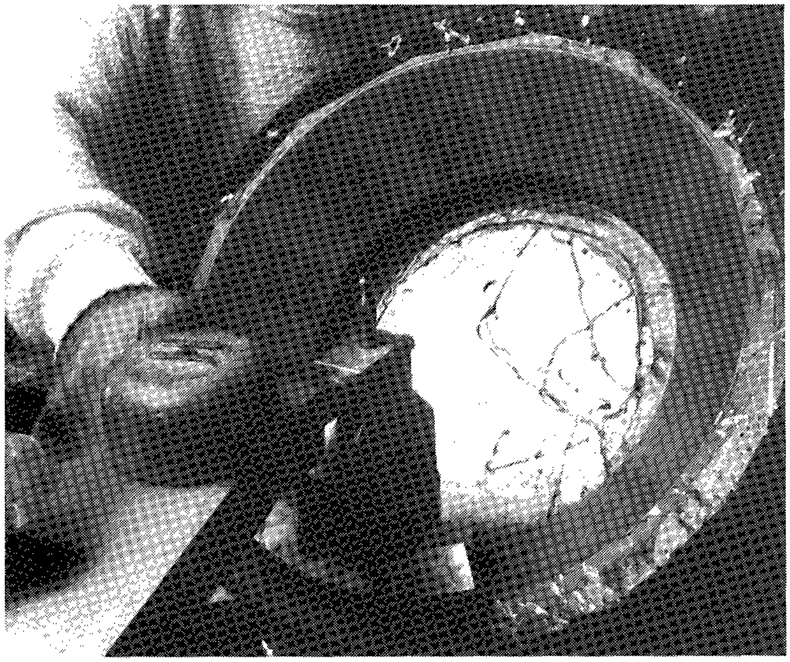

Figure 14. Annular Optic Prototype Being Optically Ground at TRW

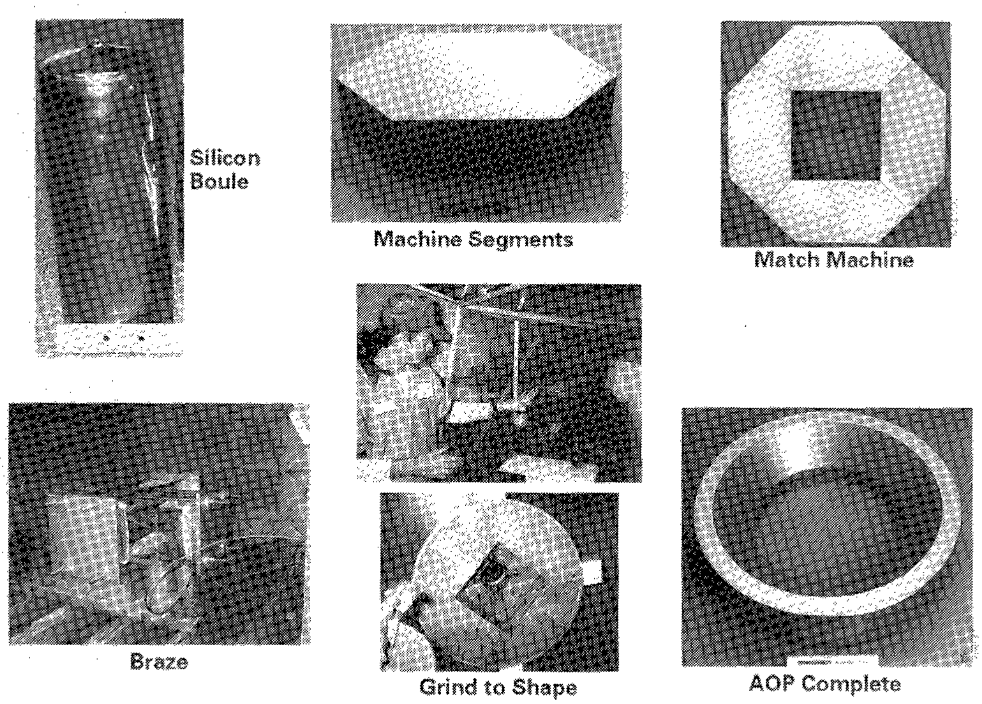

Figure 15. Annular Optic Prototype Substrate Fabrication Sequence

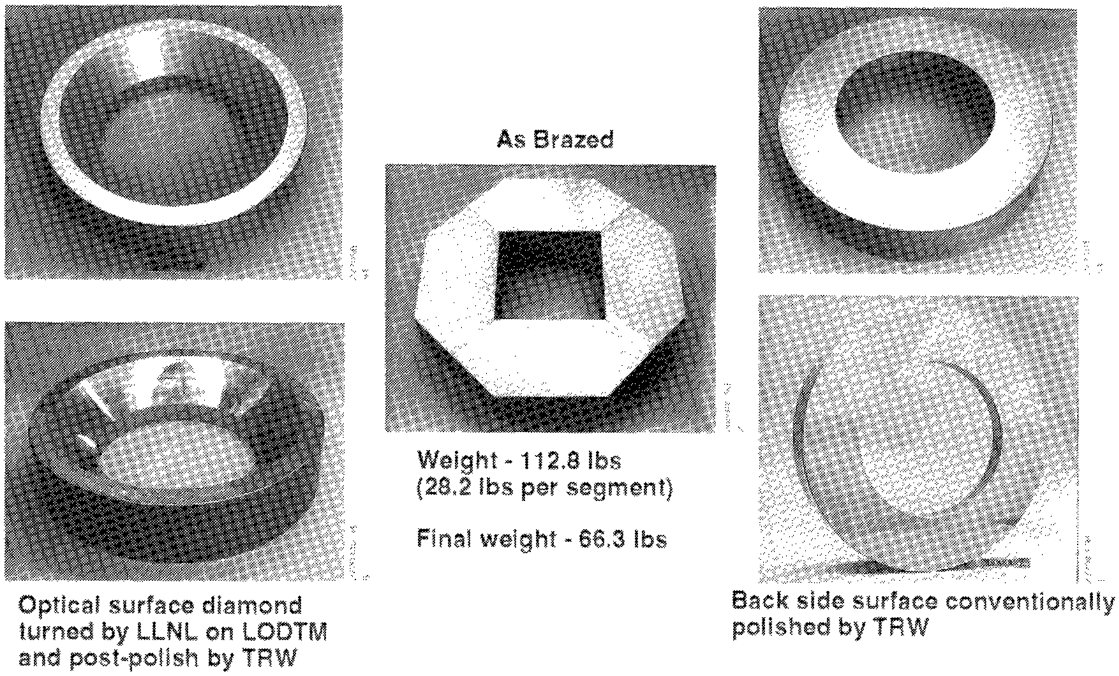

Figure 16. Annular Optic Prototype Optical Figuring